Acceptor Loads and Response of an Intervening Sand Wall Barrier from the Simultaneous Detonation of 24 Mk82 Donors[1,2]

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Abstract

Problem. The loads incident on Mk82 acceptors located two feet from the acceptor side of an intervening 3.5 foot sand wall were evaluated with the aid of hydrocodes, literature, and closed form solutions. The donor side of the sand wall was subject to the simultaneous detonation of a 4 by 6 array of 24 Mk82 donors. The leading edge of the donor array was located at a two foot standoff from the sand wall.

Approach. The problem was divided in into three regimes which included: (1) The loads promoted on the sand wall from simultaneous detonation of the donors; (2) The response of the barrier and propagation of the donor loads through the sand wall; and, (3) The interaction of the sand wall barrier with the acceptors.

Results. The extent to which the loads promoted by the donor couple to the intervening sand wall are greatly affected by the stacking configuration of the donors. This is due to the occurrence of jetting which occurs between adjacent rows of donors and the existence of rarefied regions which occurs between adjacent donor columns. The jetting results in local regions of the wall being subject to very intense pressure distributions. The rarefied regions occurring between donor columns last several 100 μsec and thwart propagation of loads toward the wall from adjacent columns of donors.

The sand wall attenuates high frequency components of the incident wave but is relatively ineffective in attenuating the low frequencies which are the major components of the incident wave. The wall becomes rapidly fluidized and the loads incident on the acceptor are to a large extent governed by the fluid-structure interaction between the multi-phase flow from the barrier debris and the stress wave response of the acceptor.

The Naval Civil engineering Laboratory (NCEL) is developing a new High Performance (HP) ordnance magazine. The goal of the magazine is to reduce the land area encumbered by Explosive Safety Distance (ESQD) arcs. This can be accomplished by limiting the Maximum Credible Event (MCE) to detonation of a single cell in the HP Magazine. This cell contains only a portion of the net explosive weight stored in the HP magazine and therefore entails smaller ESQD arcs. A critical component in the design of the HP magazine is a cell wall that prevents Sympathetic Detonation (SD) of explosives stored in adjacent HP magazine cells.

An initial part of the cell wall development effort included the analysis of a 4 by 6 array of Mk82 donors at a two foot standoff from a 3-1/2 foot thick sand wall and a 4 by 3 array of Mk82 acceptors also at a two foot standoff from the sand wall (See Figure 1). The analysis employed closed form solutions, the WONDY hydrocode, and the AUTODYN® 2D finite difference code.

The purpose of this initial phase of the analysis was to describe relevant phenomenology, identify governing parameters, and develop strategies to mitigate the environment at the acceptors.

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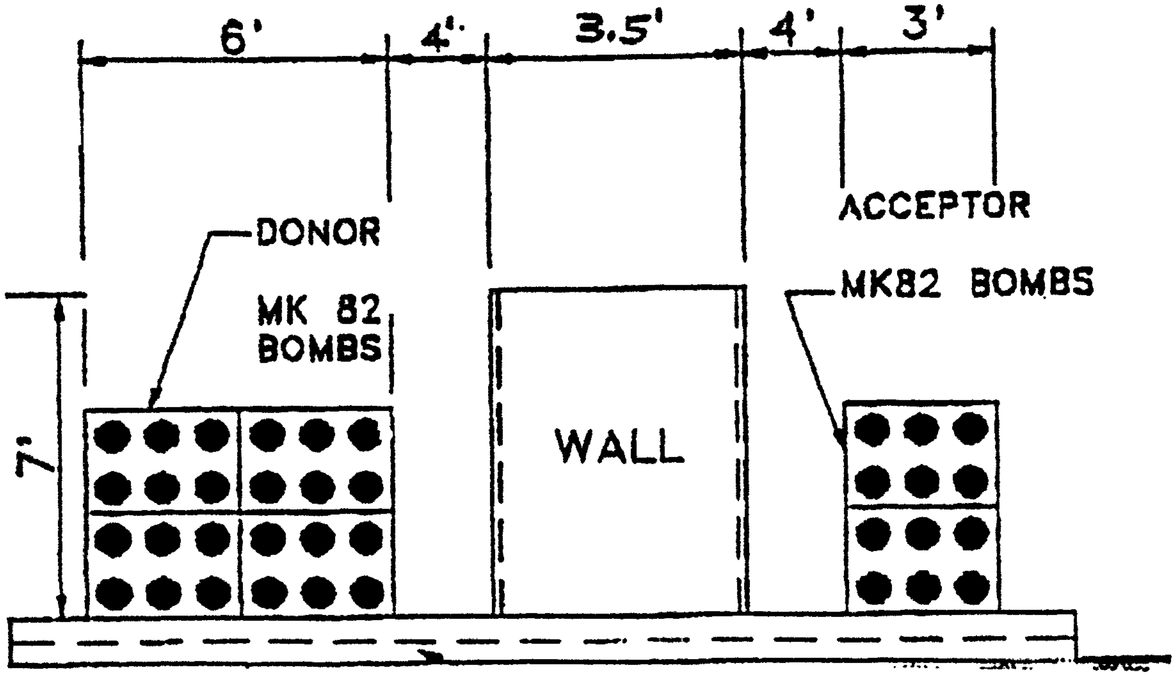

Figure 1. Geometry of Problem Analyzed.

The problem was divided into three phenomenological regions with different governing parameters and modeling considerations. The first regime considered included the donor and the donor surface of the sand wall. It was desired to describe the time resolved spatial distribution of pressures incident on the wall. The time resolution was important because sand is a dispersive medium and absorbs high frequency elements of the incident wave which promote damage. Low frequency components however propagate through the wall with minimal attenuation. The spatial distribution of incident pressures is also important since they are intense and highly non-uniform. This suggests that the environment cannot be sustained by merely increasing the flexural rigidity of the intervening wall.

The second problem regime includes the wall response. Specifically, it is desired to describe the physical state of the wall at the time of acceptor interaction and the distribution of particle velocities through the wall. It will be shown that at the time of acceptor interaction the wall is highly fluidized and only the loads promoted by a small portion of the wall near the donor surface actually couple to the acceptors.

The final problem regime which has only been superficially addressed in the subject effort includes the loads promoted by the interaction of the multiphase flow of wall debris and combustion by-products around the acceptors and the acceptor response. The significant parameters in this problem regime include the particle inertia of the wall debris and the relative velocity between the wall debris and the acceptor surfaces.

Loads Associated with Donor: Influence of Stacking Configuration

In order to describe the influence of stacking configuration, numerical experiments were conducted using the AUTODYN® code. The effort began by predicting loads at a two-foot standoff from the explosive stack for single bomb detonations in free air. The detonations corresponded to different locations in the donor stack. The AUTODYN predictions corresponded very closely with cube root scaling.

In the next series of analysis, two cases involving simultaneous detonation were considered. The first case involved two Mk82 bombs stacked parallel to the ground. The second case involved two Mk82 bombs stacked perpendicular to the ground. The pressures promoted in both cases were evaluated at the same locations as in the previous single bomb detonations. The single bomb results, at locations corresponding to the bombs in the two bomb stacks, were then superimposed and compared to the two bomb results. In general, a substantial deviation was seen for the simultaneous detonation of two bombs versus superposition of single bomb results at corresponding locations and times.

In the case of two Mk82 bombs stacked perpendicular to the ground, due to the occurrence of jetting, the predicted pressures sixteen inches above the ground and two feet away from the leading edge of the donor stack were a factor of 2-1/2 greater and the predicted impulse was 60% greater than the corresponding superposed single bomb results (See Figure 2).

In the case of two bombs stacked parallel to the ground and simultaneously detonated; the resulting pressure history is almost the same as the pressure history obtained from detonation of a single bomb corresponding to the column in the donor stack closest to the wall. This suggests that the bomb in the parallel array located farthest from the wall contributes only minimally to the loads at the wall location. Similarly, the impulse obtained by superposition of the single bomb results is about 25% greater than the corresponding two bomb simultaneous detonation (See Figure 3).

Results analogous to the two cases above were obtained for single and multi-column stacking configurations; i.e., the impulse-time histories in the vicinity of the wall location for a single column and multi-column donor are identical for the first several hundred µsec (See Figure 4). During this interval, the impulse and pressure distribution on the wall in entirely dictated by the donor column closest to the wall; i.e., the effect of adjacent donor columns is not evident.

The reason for this is suggested by the fact that at a prescribed distance along the ground, the point in time where the single and multi-column solutions bifurcate is the same at all elevations above the ground. This means that the effect occurs due to interactive effects at the explosive source as opposed to effects associated with propagation of the blast wave. When the donor model is executed in an interactive mode, rarefied regions are seen to occur between columns of the donor bombs. Pressure pulses cannot be propagated across these regions while they exist. The elapsed times during which these regions exist agree with the time intervals during which the single and multi-column results coincide and the pressure levels in directions perpendicular to the ground are correspondingly intensified.

The loads incident on the sand wall from the simultaneous detonation of 24 Mk82 bombs consist of low and high frequency components with spatial distributions that are highly non-uniform. The peak pressure and maximum specific impulse associated with the incident wave is about 11 Kb and 1.5 Mtaps respectively. These maximums occur at ground level.

Wall Response

The sand wall is a dispersive medium which means that it absorbs the energy associated with the high frequency components of the incident wave whereas the low frequency components propagate through the wall relatively unattenuated with their original pulse shape.

Figure 5 shows the attenuation of a prescribed isosceles triangular pressure pulse imposed on the donor surface of the sand wall. The peak pressure (20Kb) and shape of the prescribed pulse is identical however the pulse width is an order of magnitude different (200 µsec and 2 msec). With the exception of hydrodynamic attenuation near the acceptor surface of the wall, the 2 msec pulse manifests very little attenuation as it propagates through the wall. The 200 µsec pulse is severely

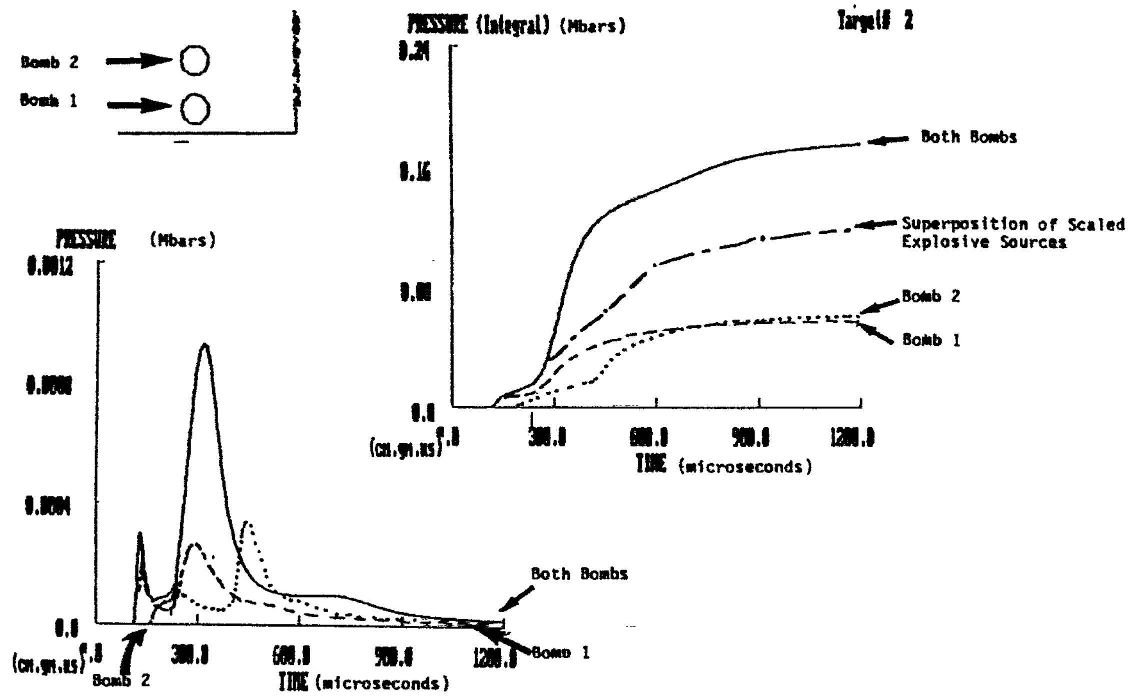

Figure 2. **Pressure and Impulse Associated with Detonation of Two Mk82 Bombs Stacked Perpendicular to Ground Compared with Superposition of Single Bomb Detonations at Corresponding Locations**

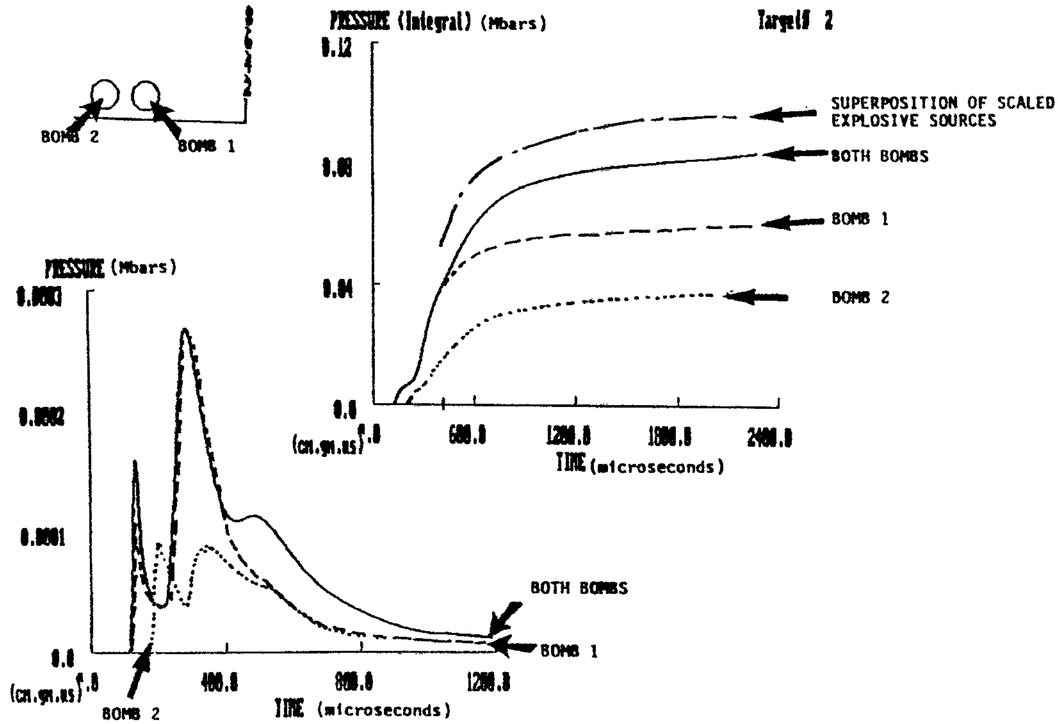

Figure 3. **Pressure and Impulse Associated with Detonation of Two Mk82 Bombs Stacked Parallel to Ground Compared with Superposition of Single Bomb Detonations at Corresponding Locations**

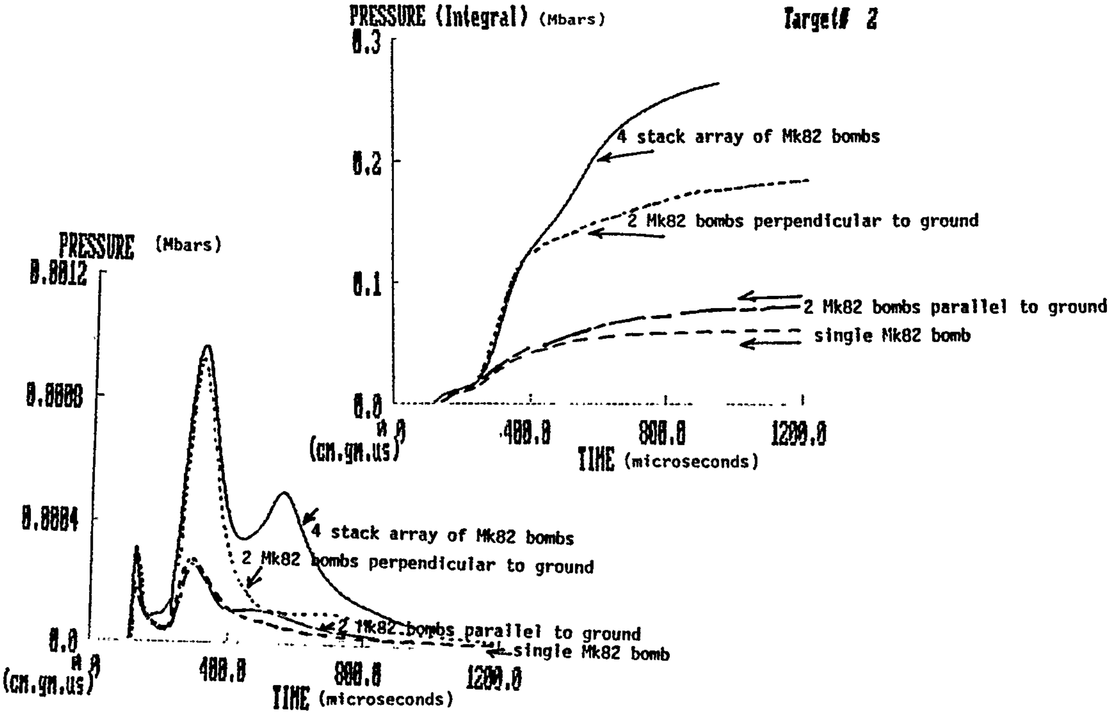

Figure 4. Impulse Histories Associated with single bomb, 1 by 2, 2 by 1, and 2 by 2 Arrays.

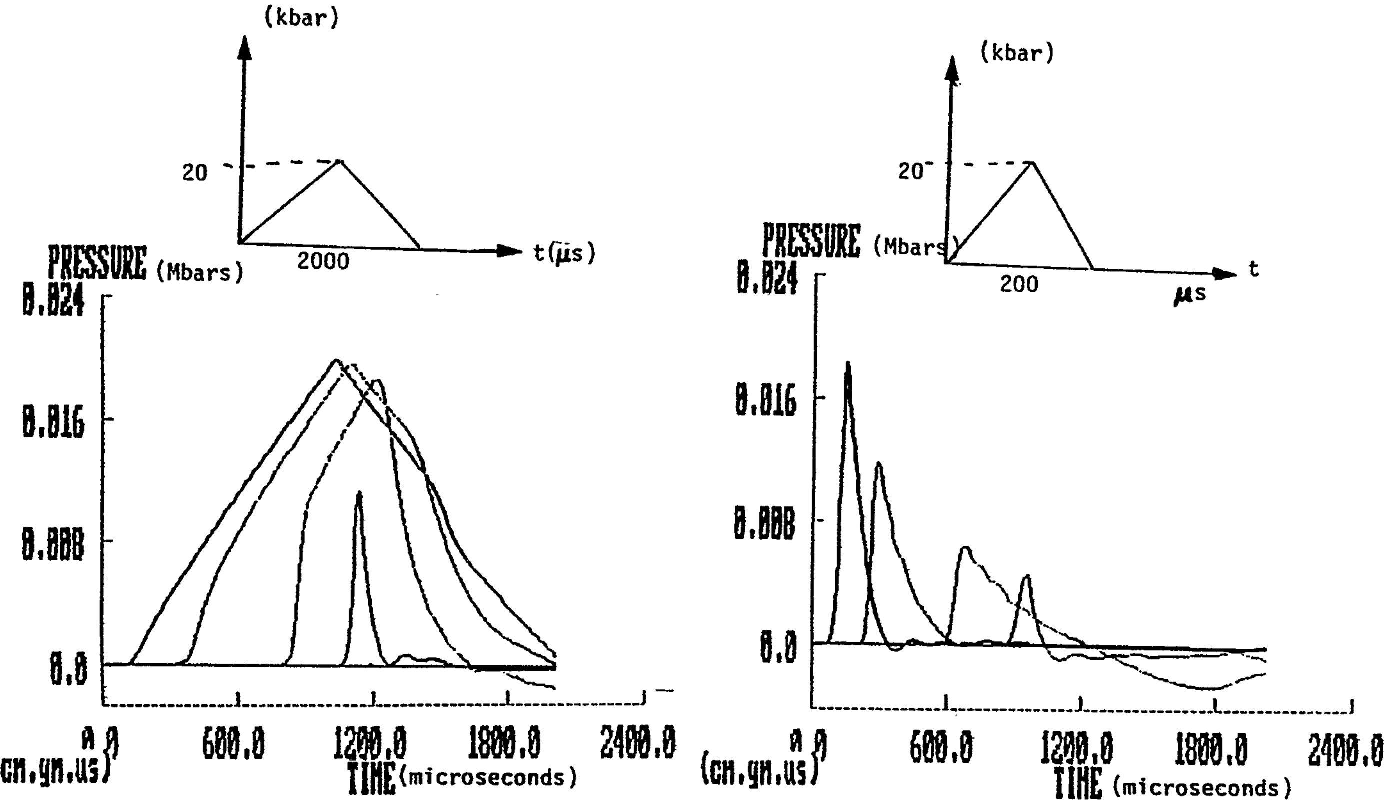

Figure 5. Attenuation of 200 μsec and 2 msec Prescribed Pulse Through Sand Wall

attenuated however with a pulse width that gets wider (with the exception of hydrodynamic attenuation near the acceptor surface) as it propagates through the wall.

The Equation Of State (EOS) employed for sand was developed to simulate 40% porosity dry quartz sand. The model assumes that the cohesive strength of the sand is negligible at pressure levels of interest. Sand also has a very small Gruneisen parameter which is ignored. The EOS is therefore simply a piecewise continuous pressure versus consolidation relation. The virgin loading curve is described by a small elastic segment up to 0.05 Kb. The elastic segment is then followed by two linear crushing regions. At pressures of 17.6 Kb the sand is assumed to be completely consolidated and the loading follows the quartz Hugoniot.

In Figure 6 the peak contact pressure resulting from the collision of a sand wall, imparted with a prescribed rigid body velocity, and a perfectly rigid boundary is considered. The one dimensional solution of this problem for contact pressure, P, is the product of ρcv; where "ρ" is the density , "c" is the sound speed, and "v" is the incident velocity of the wall. In this problem "v" is identical to the particle velocity since the wall is moving as a rigid body. The contact pressure as a function of particle velocity must be bounded by the density and sound speed for the initial state of the sand and the density and sound speed of quartz which corresponds to the final consolidated state of sand. In Figure 6 it can be seen that the corresponding AUTODYN solution for this problem lies between these two bounds. Further, the AUTODYN solution appears to originate on the curve corresponding to the initial state of sand and at higher particle velocities begins to approach the curve corresponding to the final state of sand. Figure 6 also shows the case of the explosively propelled sand wall where the particle corresponding to the acceptor side of the wall (which is also the peak particle velocity in the wall) is used.

Figure 7 shows the impulse corresponding to the cases evaluated in Figure 6. Note that although the peak pressures for the explosively propelled wall appear consistent with the corresponding rigid body formulations, the impulse is not. Rigid body motion of the sand wall results in a uniform distribution of particle velocities through the wall and a square pulse with a pulse width equal to the acoustic transit time through the wall upon contact with the boundary. In the case of the explosively propelled wall however the distribution of particle velocities is highly non-uniform resulting in a triangular pulse with a much shorter pulse width. Due to the fact that about 2/3 of the wall has fluidized prior to impact, a region of only about 10 cm in thickness from the acceptor surface contributes to the development of the pressure pulse. This region also manifests material densities that are about four times as great as the interior of the wall which only has 40 to 50% of its original material density. In comparing the explosively propelled and equivalent rigid body motion of the wall; similar peak pressures are obtained due to the similar physical state and velocity of the acceptor surface. There are significant differences however in terms of the impulse promoted which is largely due to differences in the physical state and particle velocity distribution through the remainder of the wall material.

In the case of a low frequency pulse incident on a sand wall, the particle velocity distribution is almost linear through the wall (See Figure 8). Note also that prior to interaction with the acceptor the particle velocity is maximum on the acceptor side of the wall.

At first look, this is surprising since: (1) The incident pressures are greater on the donor side of the wall than the acceptor; and, (2) The particle velocities on the donor side of the wall are subject to acceleration from the incident pulse for a longer interval of time than particles on the acceptor side of the wall. This is because it takes about 1.7 msec for the incident pulse to propagate from the donor to the acceptor surface of the wall. The particles on the donor surface of the wall are therefore subject to a more intense acceleration from the incident pulse for at least 1.7 msec longer than the particles on the acceptor surface of the wall.

On further consideration however, if we consider the one dimensional analog of the wall response

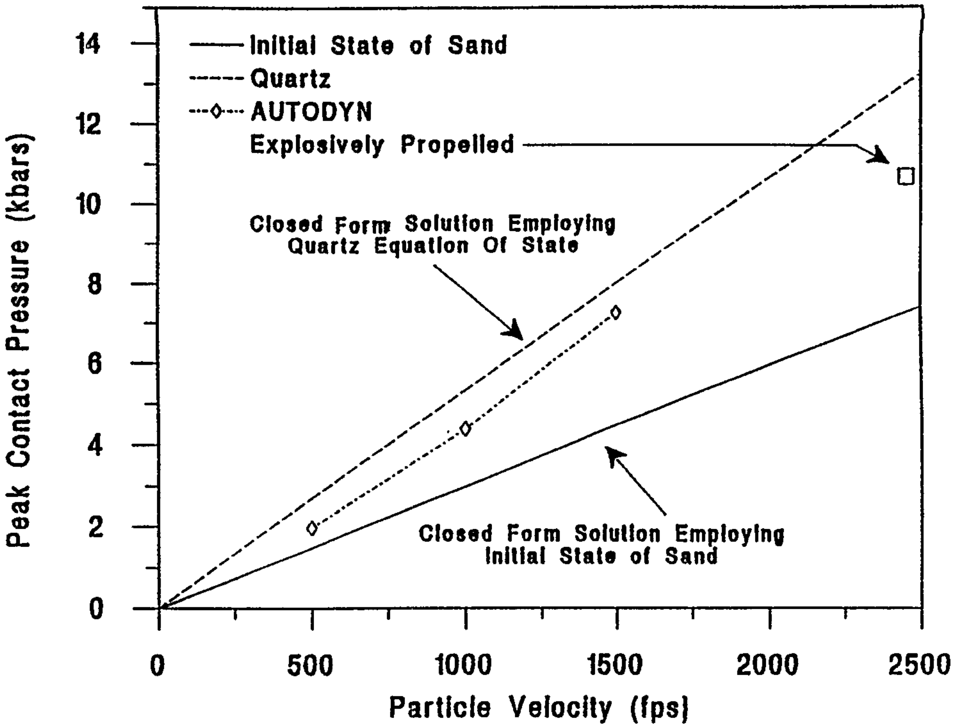

Figure 6. **Peak Contact Pressure for a Sand Wall Impacting a Rigid Boundary as a Function of Particle Velocity.**

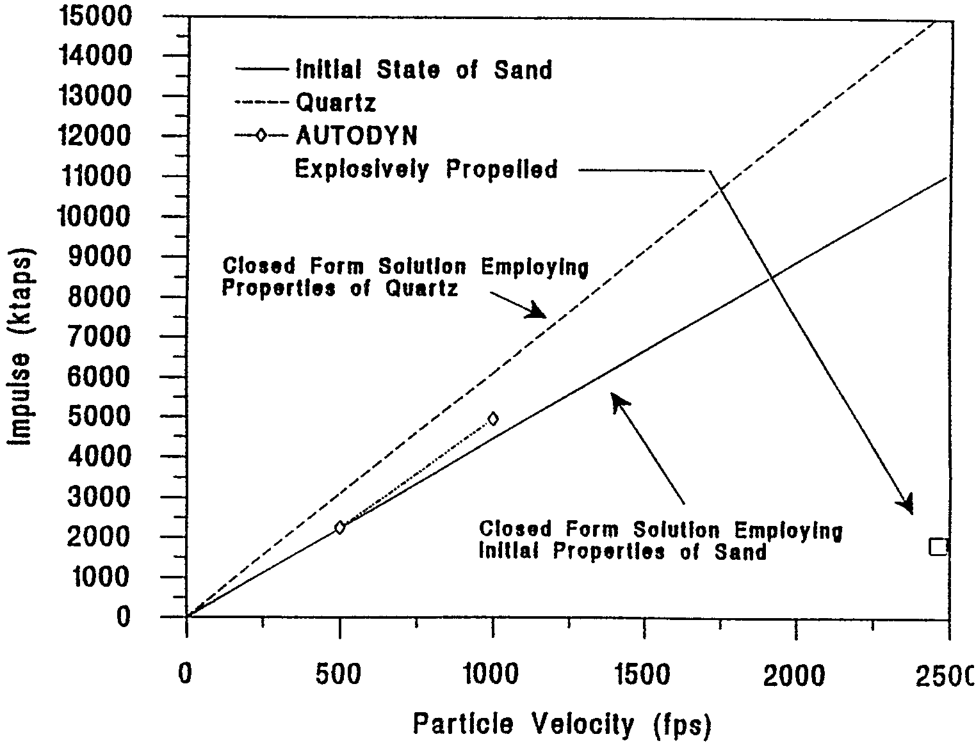

Figure 7. **Impulse for a Sand Wall Impacting a Rigid Boundary as a Function of Particle Velocity**

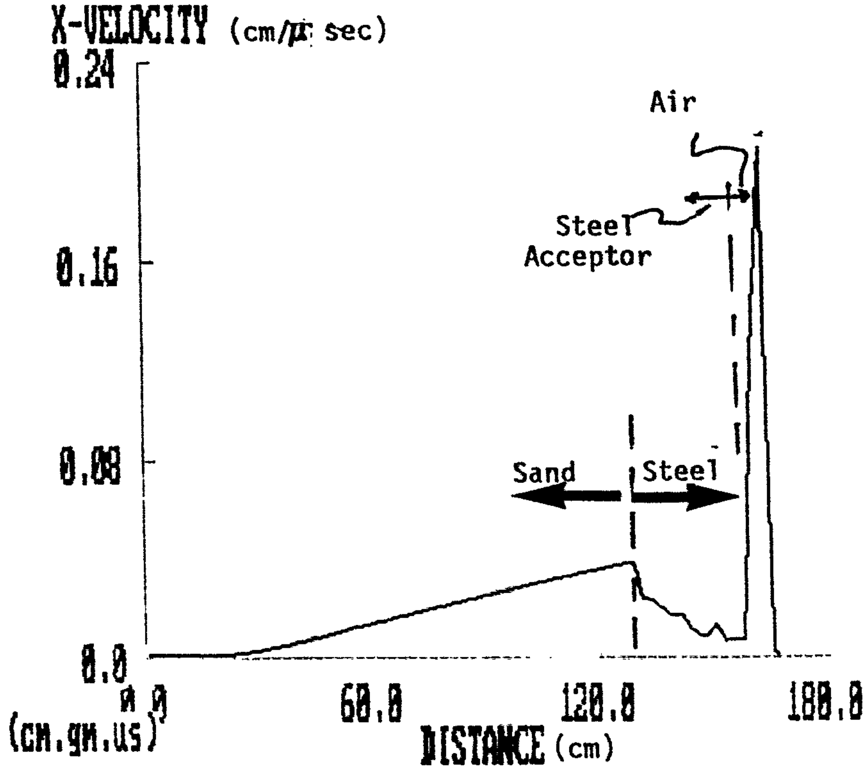

Figure 8. **Particle Velocity as a Function of Distance from the Original Location of the Donor Surface of the Wall for a Prescribed Low Frequency Pulse.**

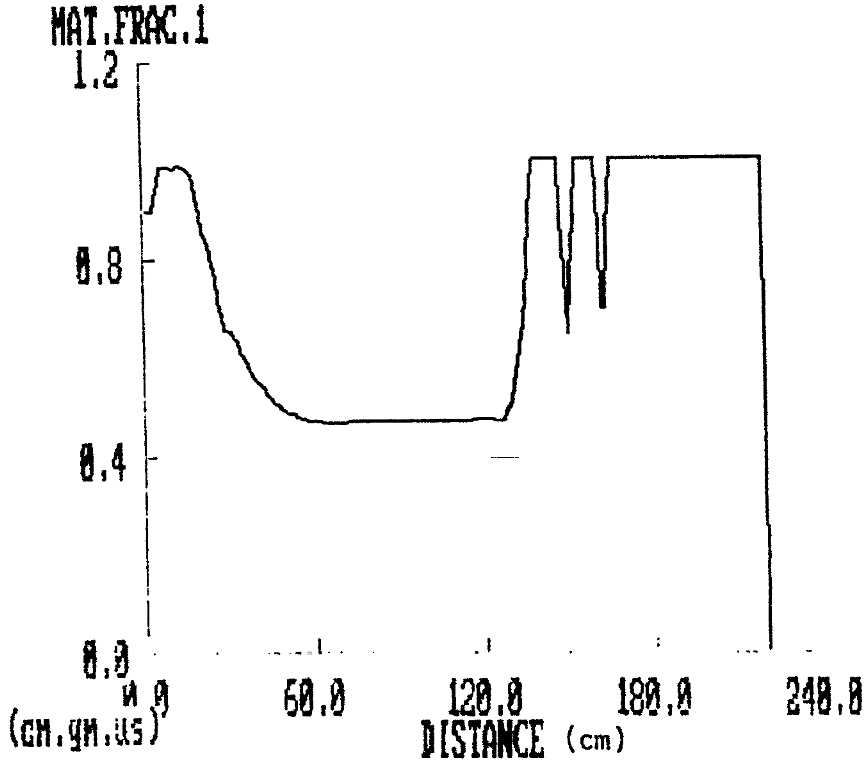

Figure 9. **Material Fraction as a Function of Distance from the Original Location of the Donor Surface of the Wall.**

in terms of an array of linear springs and lumped masses in series (parallel to the floor): the particles on the donor surface of the wall are initially accelerated and impact particles further in the wall. The particles located deeper into the wall however have a much greater associated inertia. This is due to the fact that the remaining thickness of the undisturbed wall has not been fluidized and is resisting the motion of the incident particles. The incident particles are therefore decelerated and the impacted particles gradually accelerate as this process is repeated for the duration of the pulse.

As the pulse propagates through the wall however, the remaining thickness of undisturbed wall material encountered by the pulse decreases. That is, as the pulse approaches the acceptor side of the wall, the inertia of the undisturbed wall material is significantly less than the inertia associated with wall material on the donor side of the wall. Hence, given that a low frequency pulse is only minimally attenuated as it propagates through the wall, the particles on the acceptor side of the wall, after the first transit of the incident pulse through the wall always manifest higher particle velocities than on the donor side of the wall. The linearity of the particle velocity distribution shown in Figure 8 through the wall material also suggests this mechanism since the mass inertia associated with the wall should decrease linearly with wall thickness.

The mechanism described above is associated with low frequency loadings where the constituent wall material has sufficient time to respond to the incident pulse. The wall response is fundamentally different in the case of imposed high frequency pulses where the pressure wave propagates faster than the sound speed of the material and is absorbed close to the donor surface of the wall. In this case, the material cannot respond to the incident loading and discontinuities; i.e., shock waves, are propagated into the material. The particle velocity distribution in the case of shocked materials is influenced by the *particle inertia* of the wall material (as opposed to the *wall inertia* for low frequency pulses) and generally attenuates with shock propagation distance.

For the case of a frequency spectrum consisting of both high and low frequency components the resulting particle velocity distribution will be highly non-uniform depending on the relative proportion of high and low frequency components and the dispersive character of the wall material.

In the case of the Mk82 donor scenario employing a finite tensile strength for the sand wall material, immediately prior to impact (which occurs at about 2.7 msec), a rarefied region begins to form 10 to 20 cm behind the acceptor side of the wall at about 2.1 msec. This occurs due to the incident compressive wave reflecting from the acceptor free surface of the wall in tension.

When the wall contacts the acceptors, a compressive pulse is transmitted into the acceptors and into the wall material. The pulse propagates through the acceptor and reflects in tension from the acceptor free surface. This tensile pulse then propagates back to the wall-acceptor interface. This tensile pulse superimposes on the incident compressive pulse reducing the magnitude evident at the wall-acceptor interface.

The reflected tensile pulses transmitted back into the sand material from the acceptor enhance the spallation process already under way in the acceptor side of the wall. The waves trapped in the remainder of the wall continue to generate new tensile fields from newly formed free surfaces associated with the spall planes. The spalled material starts moving with a constant acceleration but disperses in several directions and is enhanced by additional spall planes which occur in orthogonal directions.

This is particularly evident in the middle third of the sand wall which has 50% of the initial density of sand (see Figure 9). This is as compared with the donor and acceptor sides of the wall which are significantly compressed by up to a factor of 1.5 to 2 over the initial sand wall density. The stress waves within each spall plane "ring" which eventually mitigates the residual stress in each plane.

The spall planes from the first 10 to 30 cm of the acceptor side of the wall couple to the acceptor and is the major contributor to the impulse incident on the acceptor. The specific impulse associated with the highly dispersed material in the middle of the wall is very low and produces a much lower response in the acceptor. Eventually the acceptor moves faster than the residual wall material so that the remaining regions on the donor side of the wall never couple to the acceptor.

This material spreading due to spalling reduces the impact loads on the acceptor since the momentum per unit area decreases during this process. Thus, for the case of a sand wall, an increased standoff should exponentially reduce the acceptor loads. It should be noted that a tensile strength of 1000 psi was used in the sand wall models and is highly uncertain.

As the tensile strength of the sand wall approaches zero however the thickness of the spall planes should decrease eventually to the diameter of individual particles and the tensile field developed in the wall becomes negligible. Under these conditions, the environment at the acceptor resembles a continuous flow of sand material and the physics of the interaction change.

Figure 10 shows the time history of the incident pressure on cylindrical steel acceptors from a sand wall with negligible tensile strength subject to a prescribed low frequency loading. In Figure 10 the prescribed load is superimposed on the pressure history incident on the acceptor. The prescribed load represents a specific impulse of about 3.6 Mtaps. The corresponding specific impulse incident on the acceptors is about 1 Mtap and represents a reduction of about 72% from the donor environment incident on the sand wall.

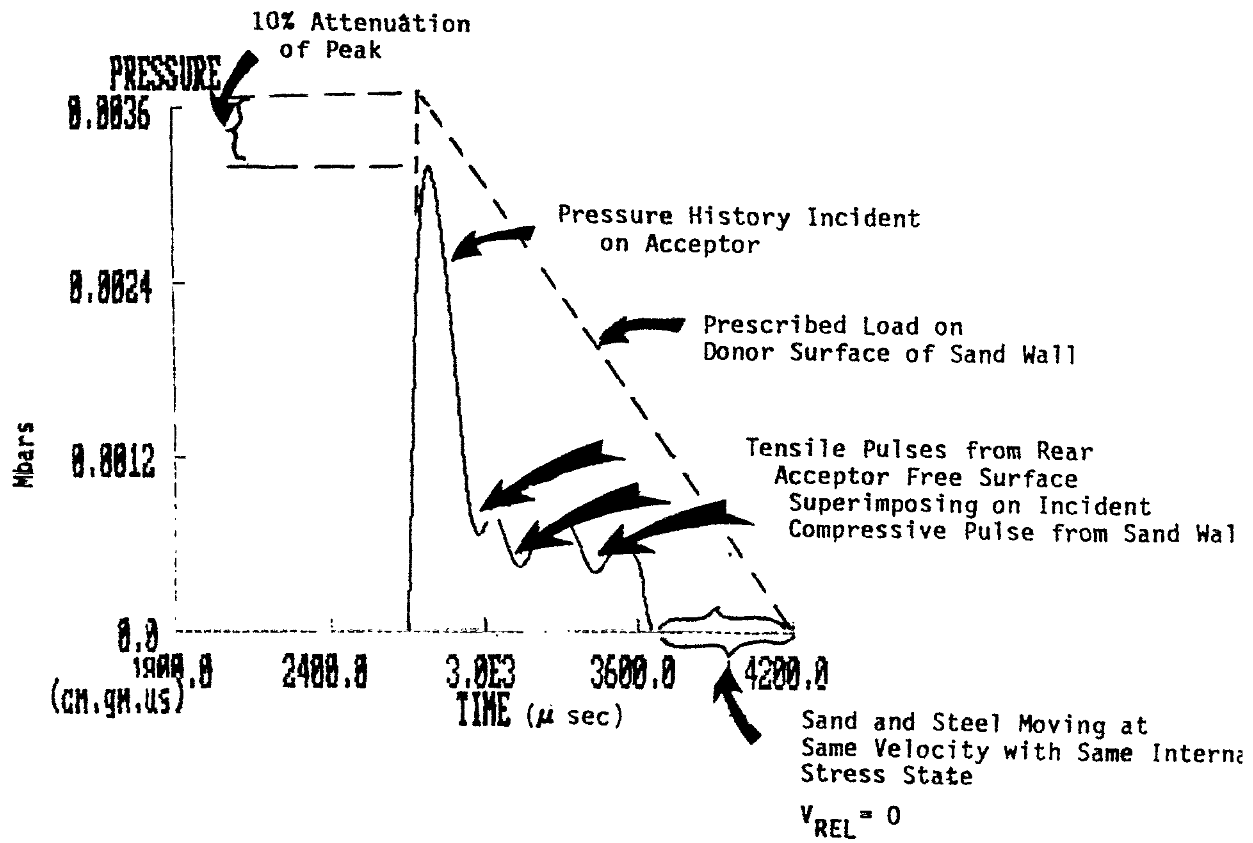

Figure 10. Pressure-time History Incident on Acceptors from a Prescribed Low Frequency Pulse

In Figure 10 the peak pressure has been attenuated by about 10% from the level incident on the cell wall. This attenuation is due to the dispersive characteristics of the sand. If the pulse were 2 msec instead of 1.8 msec, no attenuation would be observed. Similarly, if the rise time associated with the prescribed pulse was 20 instead of 150μsec, severe attenuation of this peak pressure would occur.

The modulation of the pulse after the initial compressive peak in Figure 10 is due to the incident compressive pulse reflecting in tension from the rear free surface of the acceptor. The local maxima in Figure 10 associated with this modulation occurs at intervals of 240 to 260 μsec. This elapsed time corresponds to twice the transit time in the deformed configuration of steel acceptor plus the arrival time in the sand wall.

The pulse incident on the acceptor ends when: (1) The relative velocity of the sand wall material in contact with the acceptor approaches zero -- see Figure 11; and, (2) The ringing in the steel acceptor stops due to an equilibrium stress state occurring in the sand wall material and the acceptor such that no pressure is transmitted or reflected at the wall material-acceptor interface -- see Figure 12.

Figure 11 shows the particle velocity distribution at the conclusion of the incident pulse on the acceptor. The particle velocities are plotted as a function of distance from the donor surface of the wall. At least four discrete regions can be identified on the plot. The first region on the donor side of the wall (which consists of approximately 46 per cent of the original wall thickness and mass) consists of consolidated wall material (see Figure 9). This material has a particle velocity considerably less than the acceptor or wall material in contact with the acceptor and therefore this portion of the wall material never couples to the acceptor.

This consolidated region exists because of the mechanism hypothesized previously which promotes high particle velocities on the acceptor side of the wall in the presence of low frequency load functions. That is, during the relatively long elapsed time that the donor side of the wall is subject to the incident compressive pulse, the sand particles on the donor side of the wall are accelerated and impact the undisturbed wall material. Due to the much larger inertia of this undisturbed wall material, the impacted wall region resists the motion of the particles incident from the donor side of the wall. The incident sand particles from the donor side of the wall are therefore decelerated. The only mechanism available to decelerate these sand particles is through an equal and opposite reaction force which opposes the motion of the sand from the donor side of the wall (this is the reason for the springs in the lumped mass-spring analog previously described). At the same time that this equal and opposite reaction force is generated inside the wall, the donor surface of the wall is still being compressed. Hence a consolidated region exists on the donor side of the wall as shown in Figure 9.

A second region, representing the mass equivalent of approximately 35 to 40 cm of the original wall material is also seen to extend from the consolidated region to about 120 cm at the time the pulse ends. This region which consists of highly fluidized and dispersed sand has about 40 to 50 per cent of the original sand wall material density and cannot sustain any pressure (see Figure 9). Some fraction of this region may couple to the acceptor however due to the low particle velocities, material densities, and non-existent residual stress associated with this region; the contribution of this region to the loads promoted on the acceptor is insignificant.

A third region is evident in Figure 9 which consists of planes of consolidated wall debris separated by planes of highly rarefied material. These rarefied regions are the result of ringing in the acceptor which has propagated into the sand. This region represents about 15 to 20 cm of the original sand wall thickness and mass and is the major contributor to the impulse promoted on the acceptor.

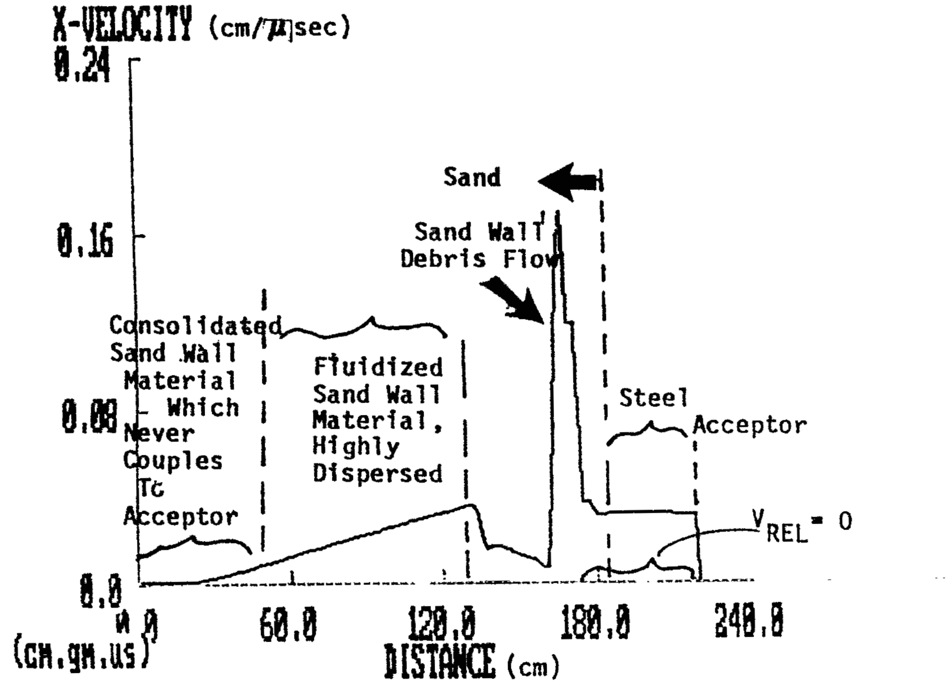

Figure 11. Particle Velocity Distribution at the Conclusion of the Pulse Incident on the Acceptor.

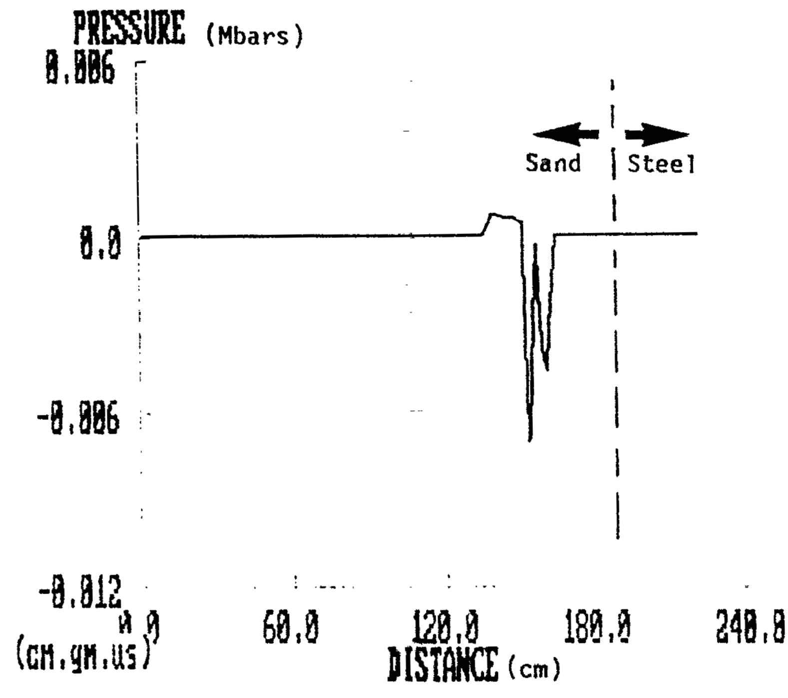

Figure 12. Pressure as a Function of Distance from the Donor Surface of the Sand Wall at the End of the Incident Pulse on the Acceptor.

Finally, there is also seen in Figure 9 a buildup of consolidated sand wall debris in front of the acceptor that is moving at the same velocity as the acceptor (see Figure 11). As is evident from the flat particle velocity profile through the acceptor and the sand wall material in this region (see Figure 11), both the acceptor and residual sand wall debris are now moving at a rigid body velocity of approximately 1300 fps. At this point, the pressure in the acceptor surface of the sand wall and the acceptor are in equilibrium and no additional stress is transmitted (see Figure 12). The incident pulse on the acceptor therefore ends.

For comparison purposes, the peak contact pressure and corresponding impulse for a water wall sustaining a prescribed rigid body and explosively propelled impact with a rigid boundary is shown in Figures 13 and 14 (analogous to Figures 6 and 7 for sand). In Figures 13 and 14 the corresponding results for a sand wall have also been surperimposed. The water wall manifests higher peak pressures than the sand wall due to the larger impedance (the product of material density and acoustic wave velocity) of water (see Figure 13). The resulting impulse of water (see Figure 14) however is much less than the sand wall. This is due to the smaller particle inertia of the water relative to the sand which allows the water to change direction more easily than sand and flow around the acceptors. This results in a much lower impulse coupling coefficient for the water wall than the sand with a correspondingly smaller impulse promoted on the acceptor.

Recommendations

Given the insight garnered from the analysis above, strategies were evolved that mitigate relevant environmental parameters for each problem region. In the donor region, recessing the floor reduces the impulse on the wall in excess of a factor of 4. For this particular problem the optimum floor recession was seen to be 3 feet.

In the case of the wall response region, three concepts were evolved. First, it was recommended that a contoured high impedance core that enhances particle velocities normal to the ground be incorporated into the wall. Second, layered materials, with mechanical stiffness and masses determined from a lumped mass spring model alluded to above. should be incorporated into the wall in order to achieve favorable particle velocity distributions through the wall thickness. Finally, it was shown that a connection from the wall to the surrounding structure that survives 1 msec. will reduce the impulse on the acceptor by at least 35%. This was estimated from an extremely conservative analysis and it is likely that the benefits of a properly designed connection will greatly exceed this preliminary estimate.

In terms of impulse coupling to the acceptor; minimizing the particle inertia of the wall debris material is desirable. It was also recommended that an N-particle, lumped mass spring model be developed in conjunction with a multilayer shell model to describe the rigid body displacement and non-rigid body deformation of the acceptors. This in turn would allow explicit determination of impulse coupling coefficients for different locations in the acceptor stack.

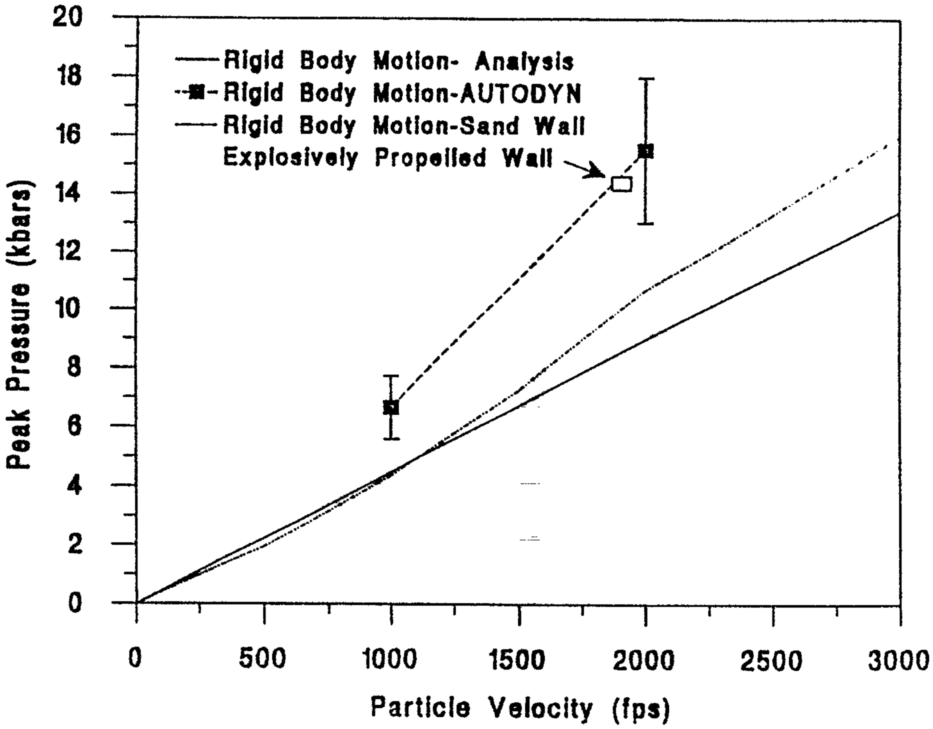

Figure 13. **Peak Contact Pressure for a Water Wall Impacting a Rigid Boundary as a Function of Particle Velocity.**

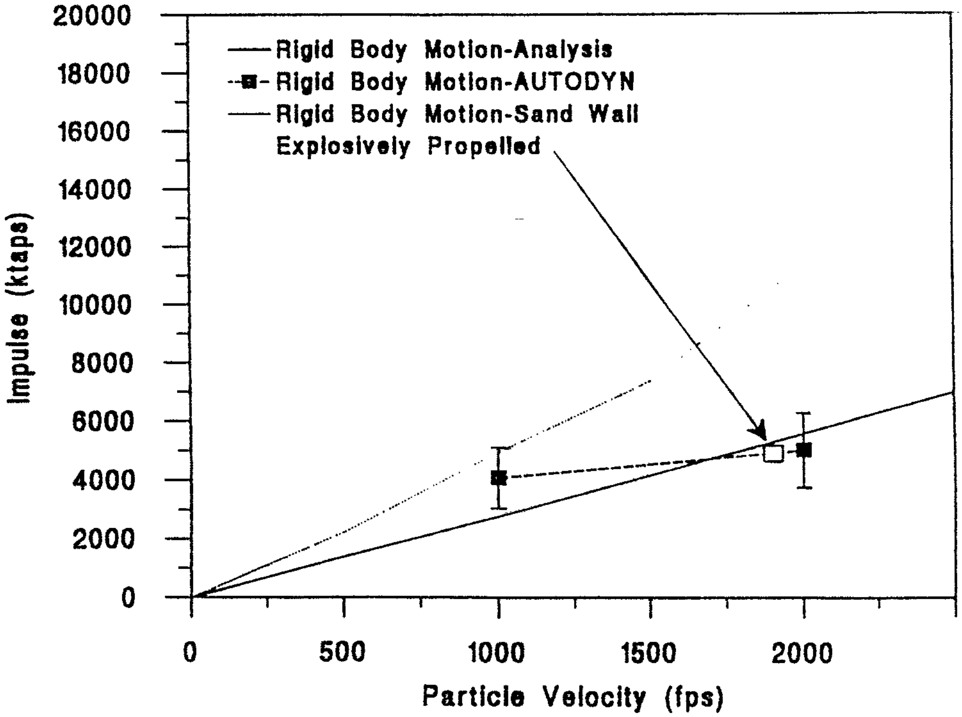

Figure 14. **Impulse for a Water Wall Impacting a Rigid Boundary as a Function of Particle Velocity**